2:30pm-2.50pm:

Radiation Hydrodynamic Simulation of Laser-produced Tin Plasmas

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Gigaphoton

NEDO New Energy and Industrial Technology Development Organization

Prof. T. Higashiguchi
and their colleagues (Utsunomiya U.)

How to increase the EUV conversion efficiency (CE)

EUV[1] Conversion efficiency (CE)

[1] 13.5nm wavelength with 2% bandwidth

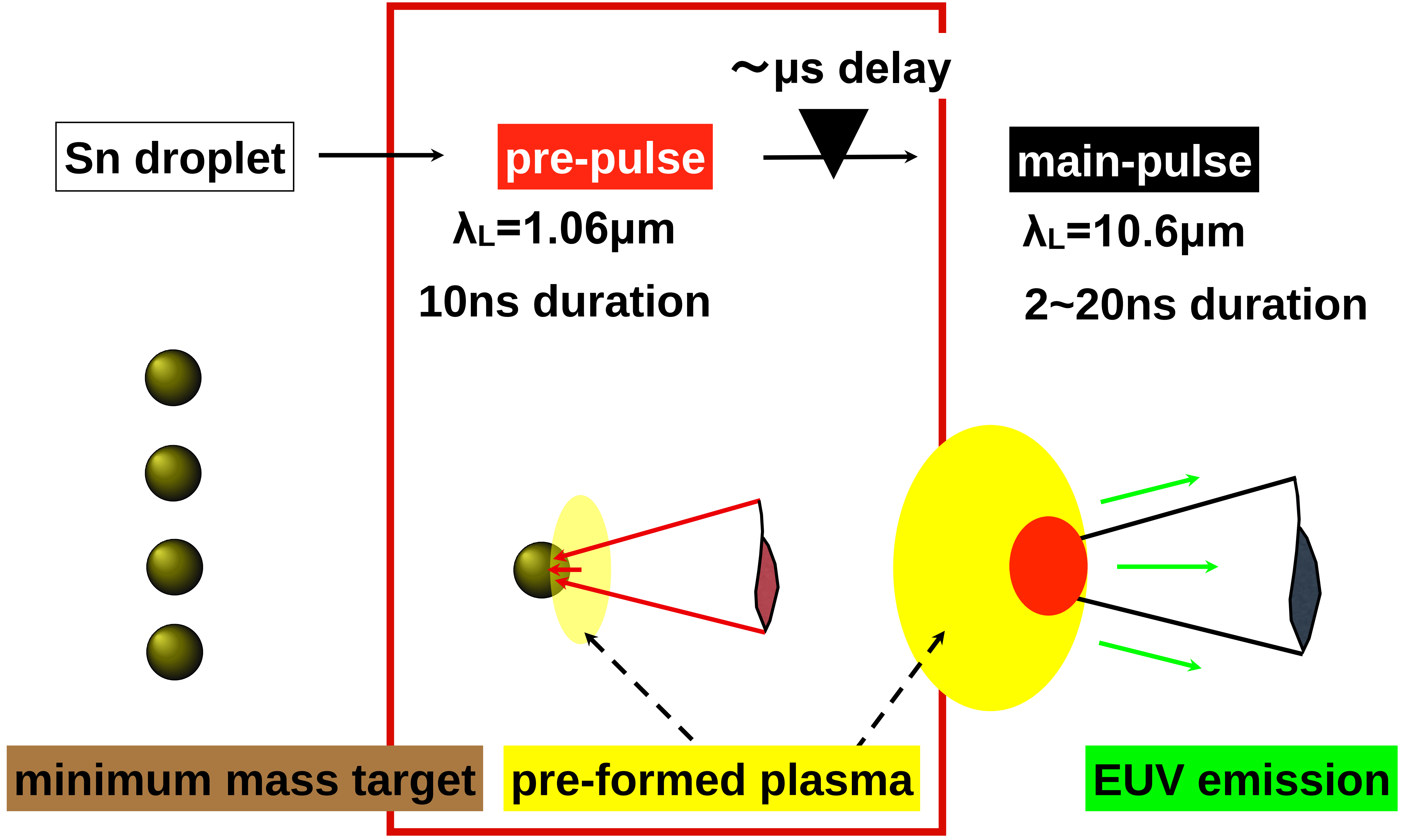
= **Laser absorption fraction** × **Conversion efficiency to radiation** × **EUV spectral efficiency**

Laser absorption fraction	Conversion efficiency to radiation	EUV spectral efficiency
absorbed laser energy / input laser energy	x-ray emission energy / inputed energy into plasma	EUV emission energy / x-ray emission energy

	CE		Laser absorption fraction	Conversion efficiency to radiation	EUV spectral efficiency
past	3%	=	50%	50%	12%
			↓	↓	↓
current	5%	=	80%	50%	12%

Successfully improved by double pulse scheme

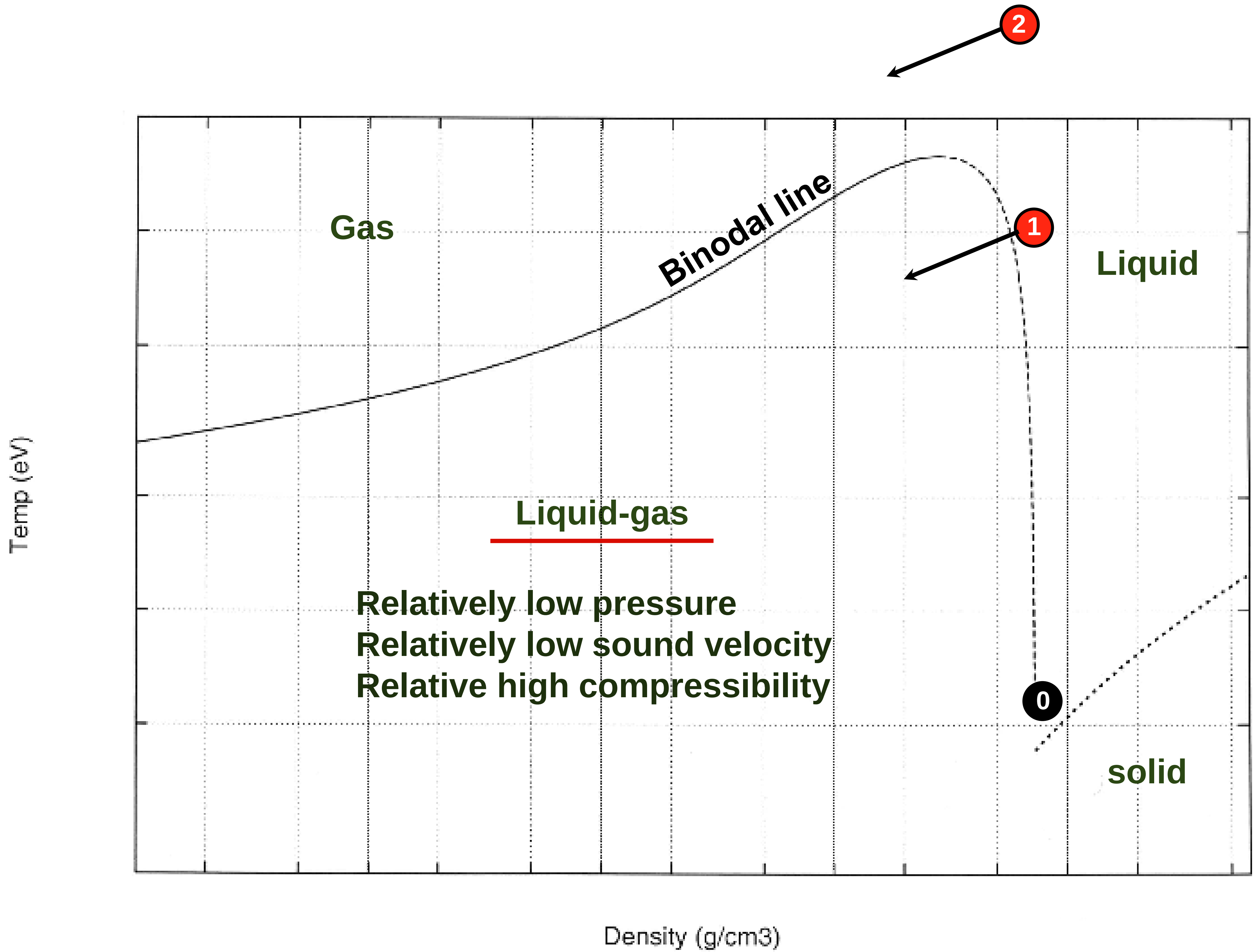
Double pulse irradiation scheme



- **We have improved the equation of state (EOS) and opacity data tables that are used in the R. hydro code.**

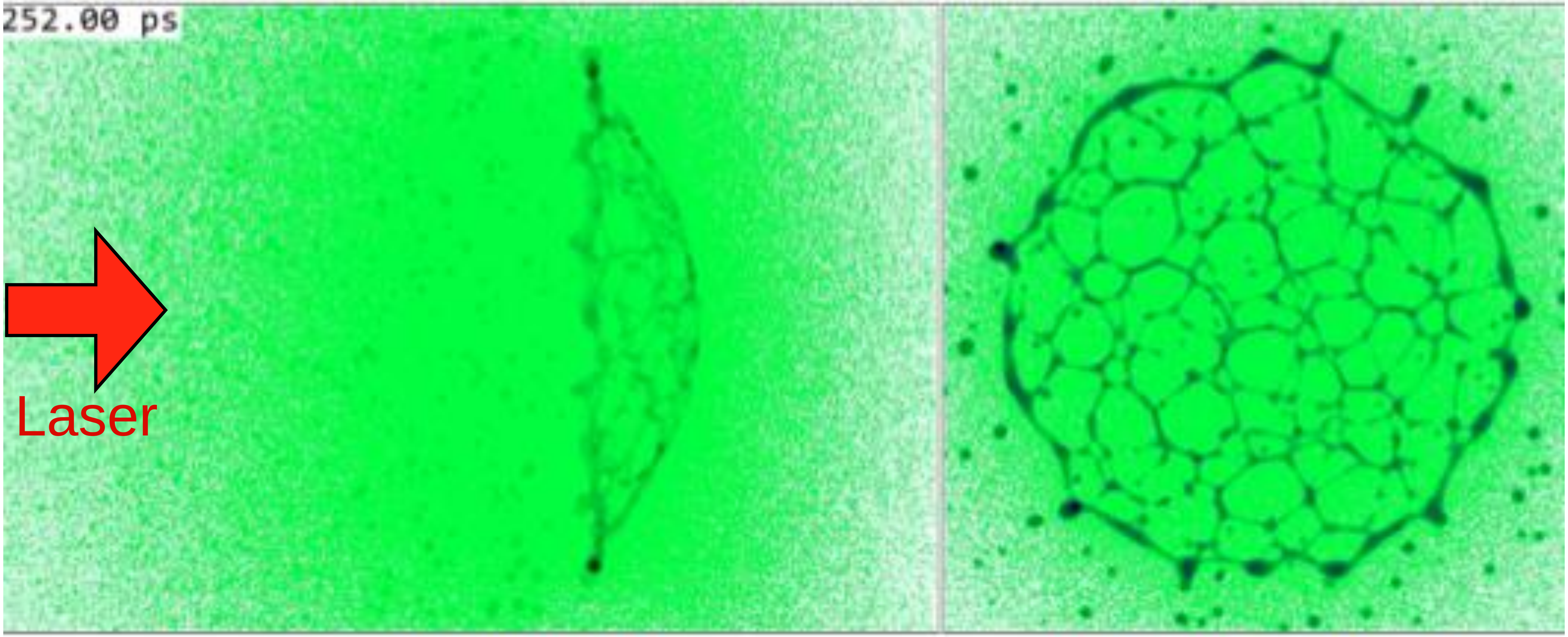
- **We have developed 2D radiation hydrodynamics code in the conservative form**

- **We have developed M1 radiation transport routine to simulate the radiation transport accurately.**



We have to consider the liquid-gas mix phase whose property is non-ideal.

Molecular dynamics simulation shows the tin in the liquid-vapor phase



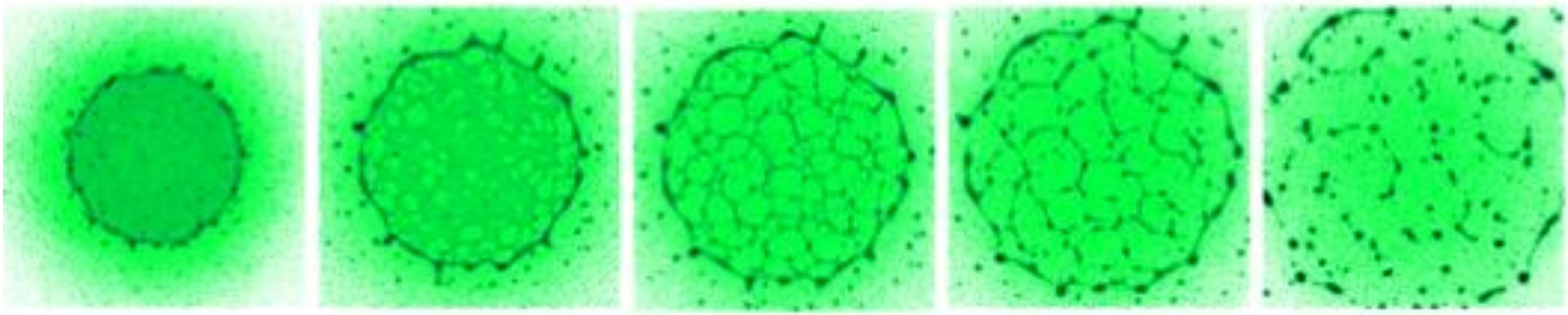
Side view/shadow of density

View/shadow from the right

Universal evolution of material geometry triggered by ultrafast energy deposition:

- 3D large droplet
- 2D liquid shell
- 1D net of threads
- 0D atoms + 3D small droplets => a new pulse repeats above

Fragmentation of expanding liquid shell



Universal evolution of material geometry triggered by ultrafast energy deposition:

- 3D large droplet
- 2D liquid shell
- 1D network of threads
- 0D atoms + 3D small droplets

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

Momentum equation

$$\frac{\partial (\rho u + F/c^2)}{\partial t} + \nabla \cdot (\rho u u + p + \mathsf{P}) = 0$$

Energy equation

$$\frac{\partial (\varepsilon + E)}{\partial t} + \nabla \cdot [(\varepsilon + p) u + F] = u \cdot (\nabla \cdot \mathsf{P})$$

Radiation transport equation

$$\frac{\partial E_\nu}{\partial t} + \nabla \cdot F_\nu = 4\pi \eta_\nu - c\chi_\nu E_\nu$$

$$\frac{1}{c}\frac{\partial F_\nu}{\partial t} + c\nabla \cdot \mathsf{P}_\nu = -\chi_\nu F_\nu$$

Ion temperature equation

$$\rho c_{vi} \frac{DT_i}{Dt} = -p_{thi} \nabla \cdot u - Q_{ei} + \nabla \cdot [illegible] \nabla T_i$$

Electron temperature equation

$$\rho c_{ve} \frac{DT_e}{Dt} = -p_{the} \nabla \cdot u + Q_{ei} + \nabla \cdot \kappa_e \nabla T_e$$

$$+ \nabla \cdot (\kappa_r \nabla T_r) + S_e + S_r$$

Hydro pressure

$p =$ [illegible]

Radiation energy density

$$E = \int_0^\infty \int_{4\pi} \frac{1}{c} I_\nu \, d\Omega \, d\nu = \int_0^\infty E_\nu \, d\nu$$

Radiation energy flux

$$F = \int_0^\infty \int_{4\pi} I_\nu \Omega \, d\Omega \, d\nu = \int_0^\infty F_\nu \, d\nu$$

Radiation pressure tensor

$$\mathsf{P} = \int_0^\infty \int_{4\pi} \frac{1}{c} I_\nu \Omega\Omega \, d\Omega \, d\nu = \int_0^\infty \mathsf{P}_\nu \, d\nu$$

Radiation heating source term

$S_r = -\int_0^\infty$ [illegible] $d\nu$

η_ν **emissivity** χ_ν **abs coeff.** Opacity

EOS

[illegible] (ρ, T_i) **ion pressure**

[illegible] $(\rho,$ [illegible]$)$ **electron pressure**

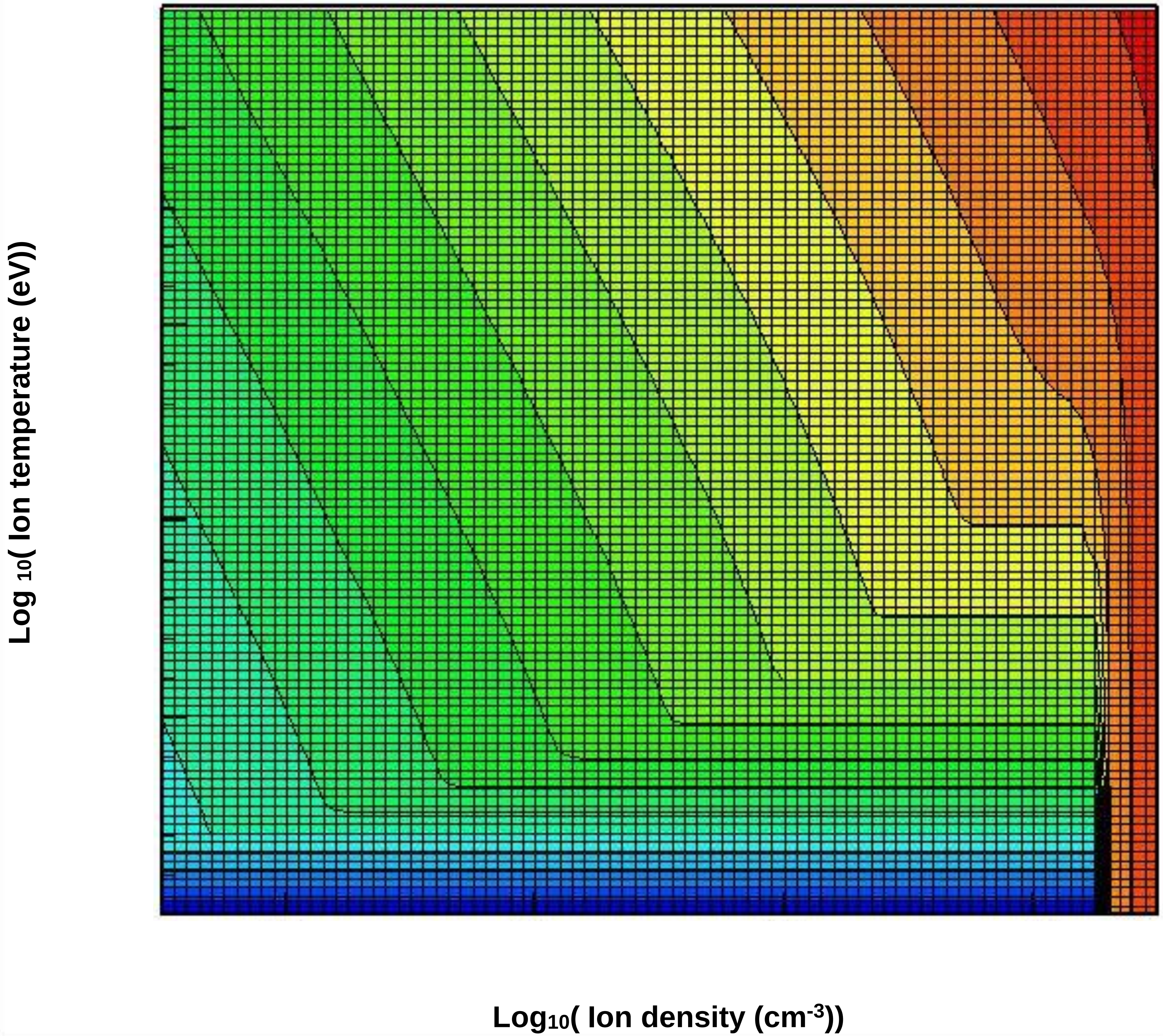
$c_{vi}(\rho, T_i)$ **ion specific heat**

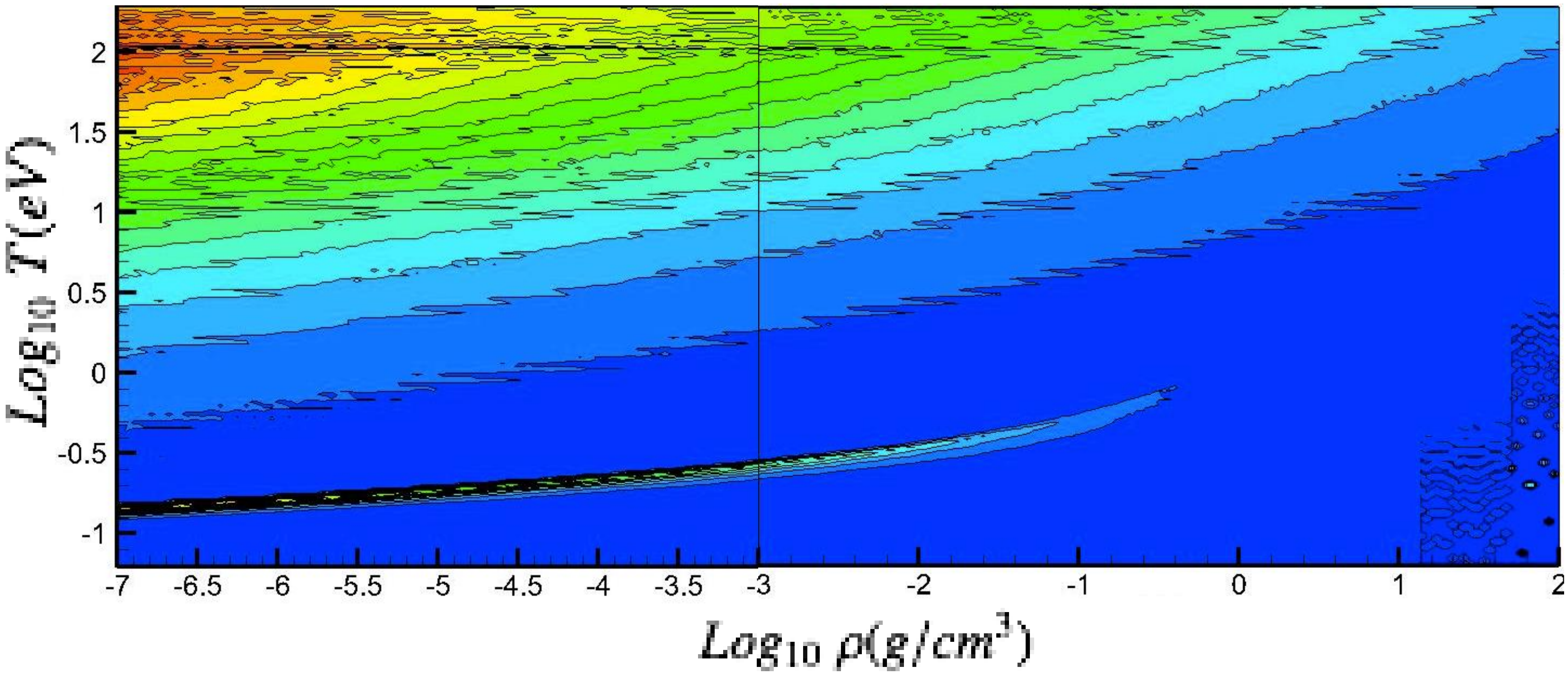
$c_{ve}(\rho,$ [illegible]$)$ **electron specific heat**

[illegible] $= p_{thi}(\rho, T_i)$

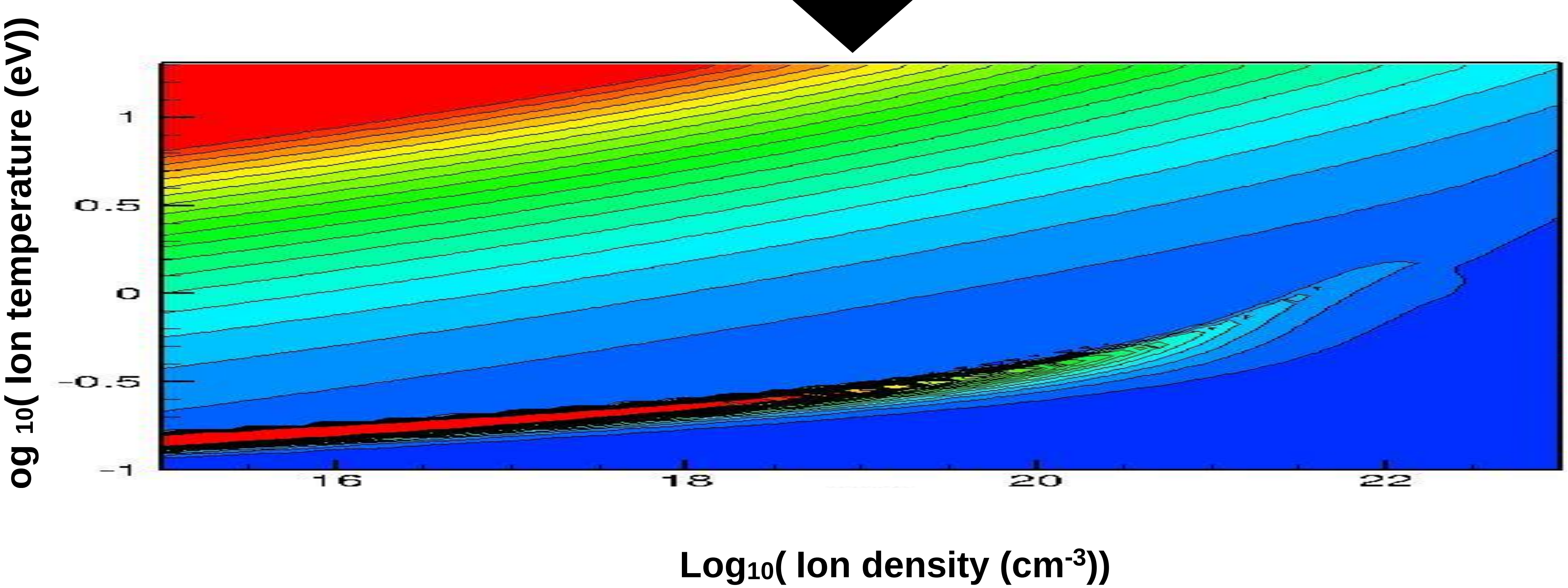
[illegible] $= p_{the}(\rho, T_i)$

Pressure EOS





specific heat $C_V = \left(\frac{\partial E}{\partial T}\right)_\rho$



Non-conservative scheme v.s. conservative scheme

Non conservative e.g.,CIP $f = (\rho, u, T)^T$

$$\frac{\partial f}{\partial t} + \underbrace{(u \cdot \nabla) f}_{\text{advection term}} = \underbrace{g}_{\text{Non-advection term}}$$

T can be treated independent value

Two temperature and thermal conduction can be easily treated.

Big error for large time steps

Conservative $U = (\rho, \rho u, \rho e_t)^T$ $F = (\rho u, \rho u^2 + P, \rho(e_t + P)u)^T$

Conserved value

Flux

$$\frac{\partial U}{\partial t} + \nabla \cdot F = 0$$

ρ: Density,
u: Velocity,
T: Temperature,
P: Pressure,
$\rho e_t = \rho e + 1/2\ \rho u^2$: Total energy density
e : Internal energy

T is dependent variable, and given by EOS.

$\longrightarrow$ $\rho e = \rho e_t - \frac{1}{2}\rho u^2$

$\longrightarrow$ $T(\rho, e)$

Sometimes T becomes negative

Conserved values U are numerically conserved.

We would like to develop the hydro in the conservative form, with using T

We solve both conservative form of hydro equation and the energy equations of non-conservative form.

Conserved form of hydro equations

$$\frac{\partial U}{\partial t} + \nabla \cdot F = 0$$

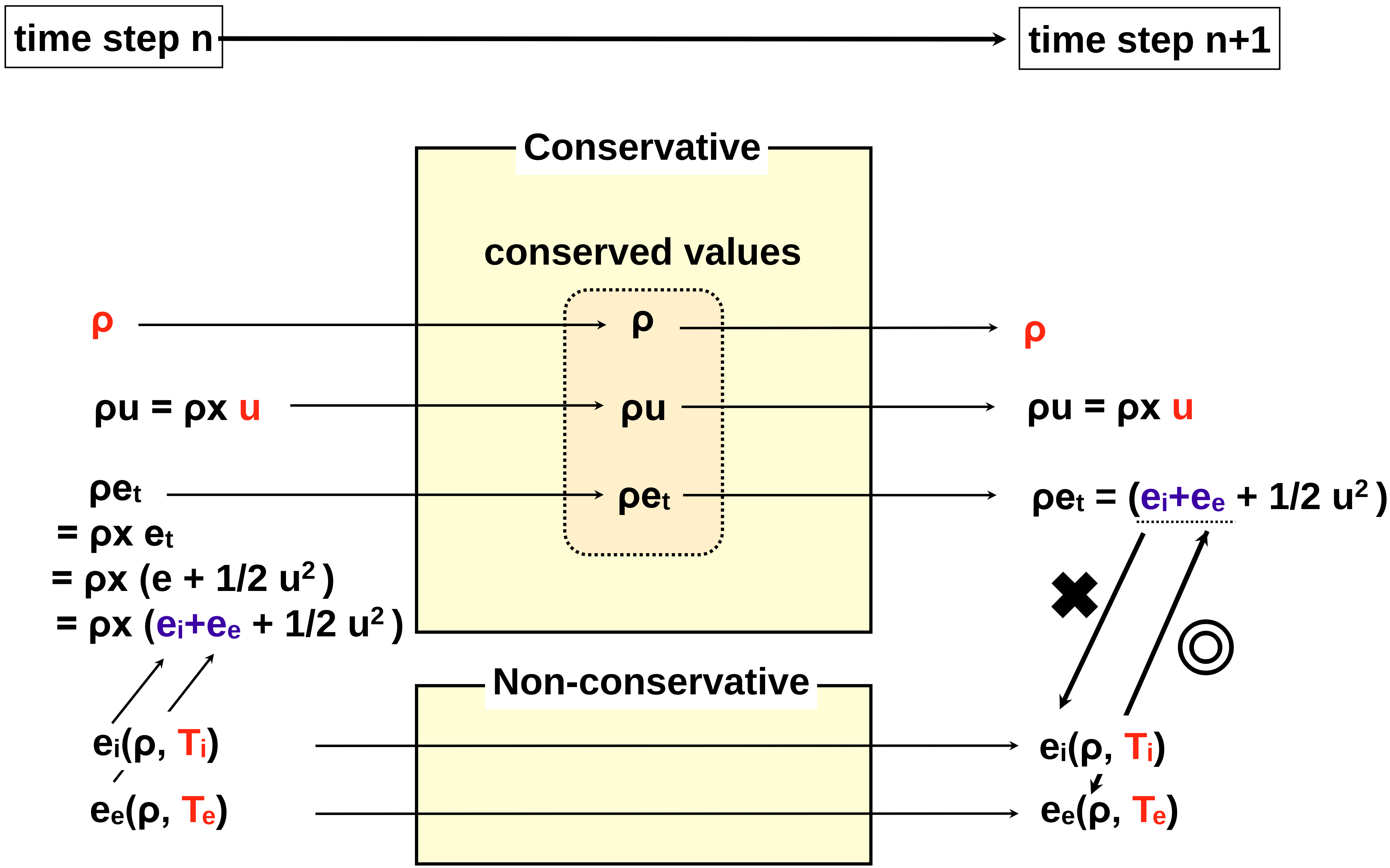
$U = (\rho, \rho u, \rho e_t)^T$

$F = (\rho u, \rho u^2 + P, \rho(e_t + P)u)^T$

$$\frac{\partial e_i}{\partial t} + \nabla \cdot e_i u = -p_i \nabla \cdot u \qquad \frac{\partial e_e}{\partial t} + \nabla \cdot e_e u = -p_e \nabla \cdot u$$

temperature equation in the non-conserved form

$$\frac{\partial T_i}{\partial t} + u \cdot \nabla T_i = \frac{-p_{thi}}{\rho c_{vi}} \nabla \cdot u \qquad \frac{\partial T_e}{\partial t} + u \cdot \nabla T_e = \frac{-p_{the}}{\rho c_{vi}} \nabla \cdot u$$



Energy equation is now in non-conservative form.
However, this method can simulate the EUV plasma so accurately.

Moment equation of radiation transport

$$\boxed{\frac{\partial E_\nu}{\partial t} + \nabla \cdot F_\nu = 4\pi\eta_\nu - c\chi_\nu E_\nu}$$

$$\frac{1}{c}\frac{\partial F_\nu}{\partial t} + \boxed{c\nabla \cdot \mathsf{P}_\nu = -\chi_\nu F_\nu}$$

Flux-limited Diffusion

P1, M1, General f

Eddington tensor

P = f E

$$E = \int_0^\infty \int_{4\pi} \frac{1}{c} I_\nu \, d\Omega d\nu = \int_0^\infty E_\nu \, d\nu$$

Radiation energy density

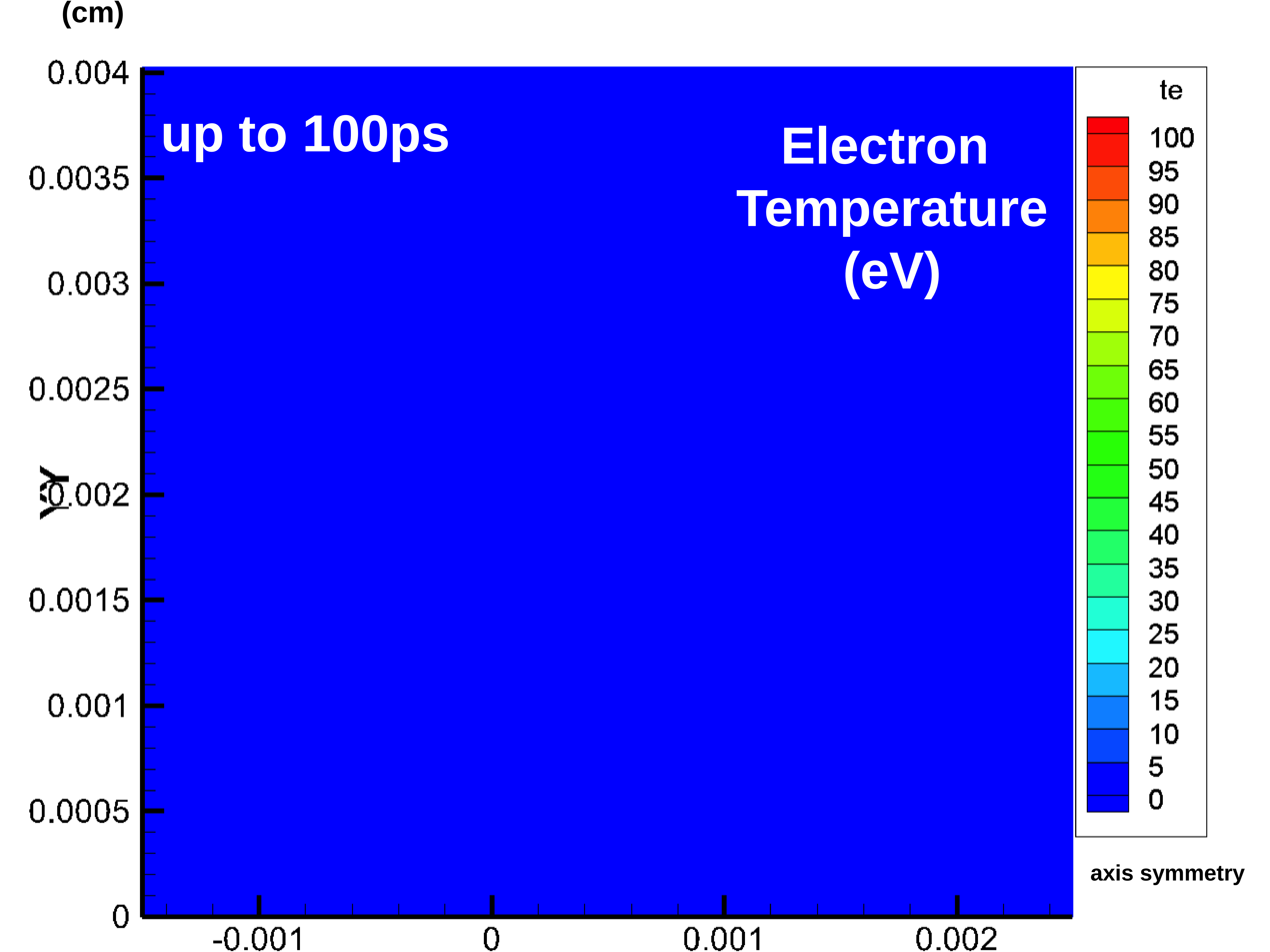
$$F = \int_0^\infty \int_{4\pi} I_\nu \Omega d\Omega d\nu = \int_0^\infty F_\nu \, d\nu$$

Radiation energy flux

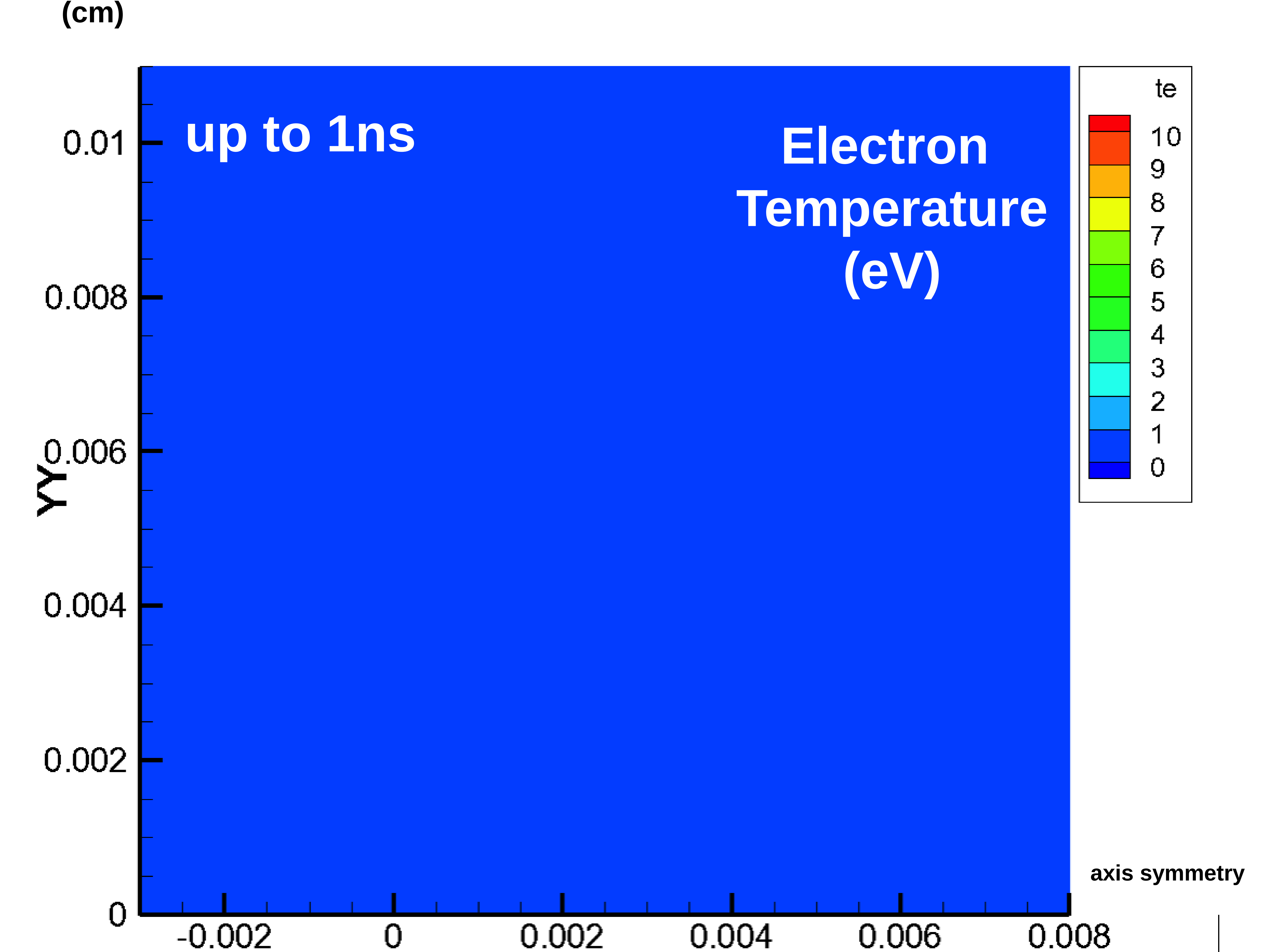
$$\mathsf{P} = \int_0^\infty \int_{4\pi} \frac{1}{c} I_\nu \Omega\Omega d\Omega d\nu = \int_0^\infty \mathsf{P}_\nu \, d\nu$$

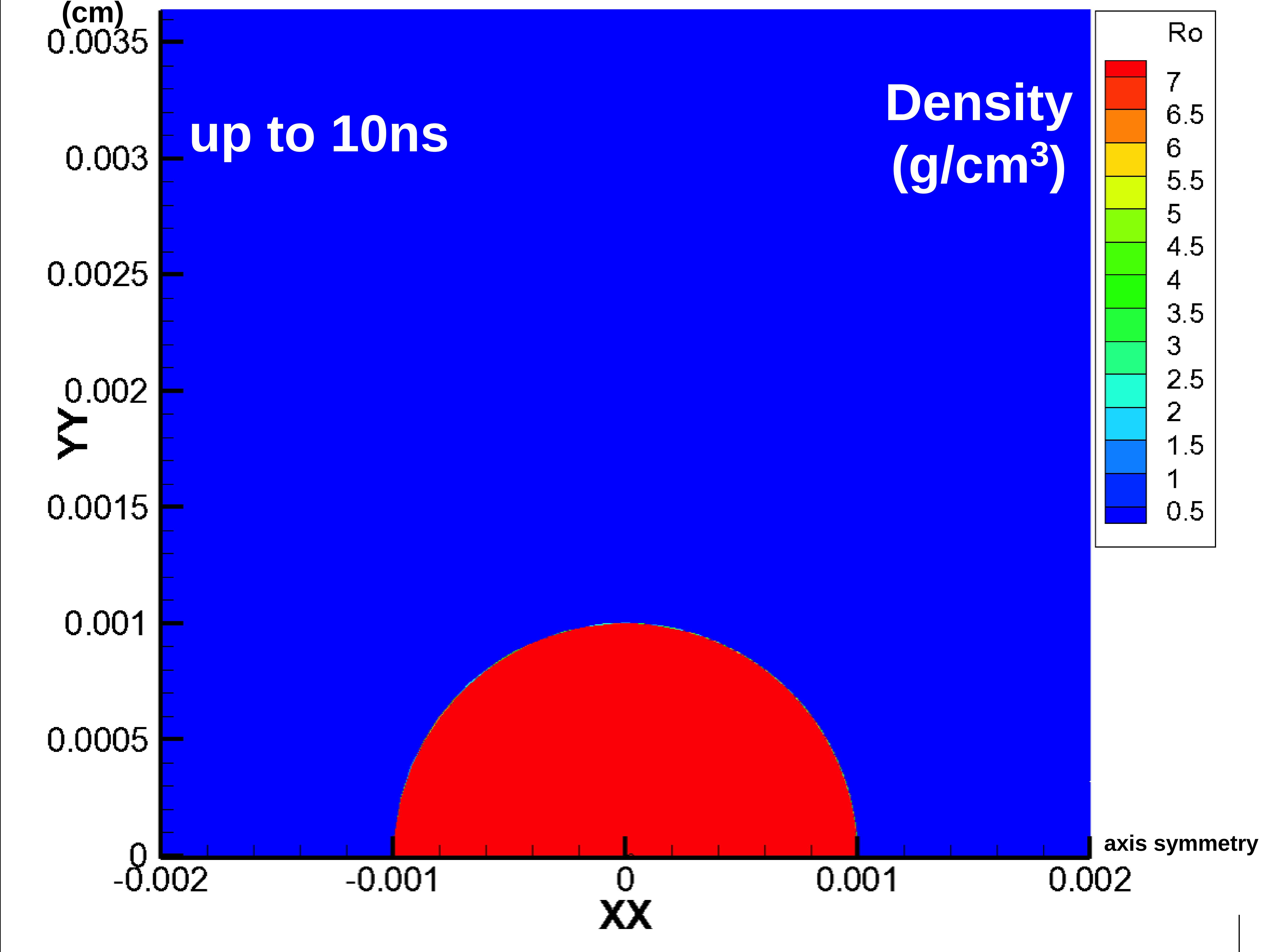
Radiation pressure tensor

10ps pre-pulse

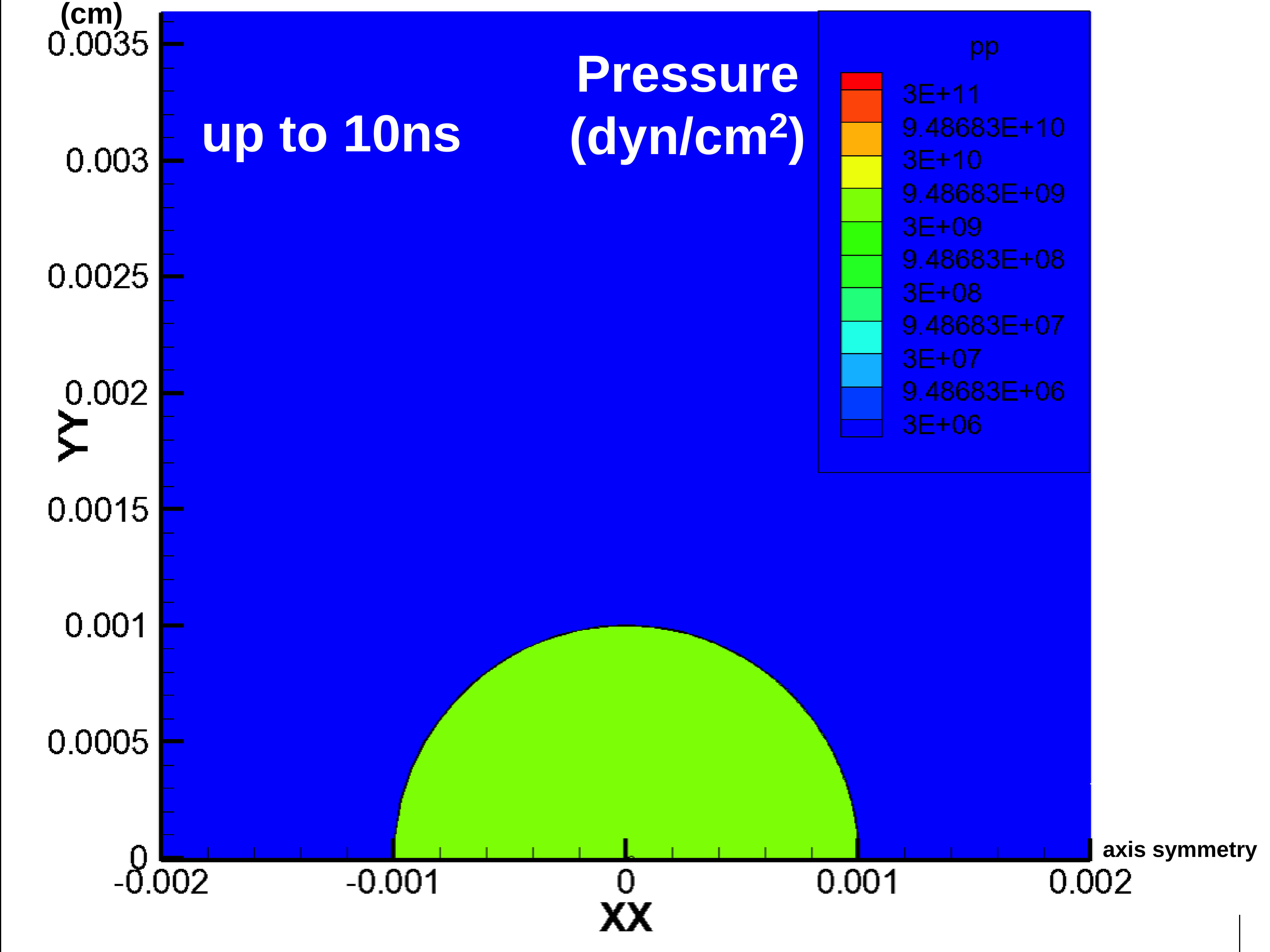


(cm)
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Y
up to 100ps
Electron Temperature (eV)
te
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
axis symmetry
-0.001
0
0.001
0.002


(cm)
up to 1ns
Electron Temperature (eV)
te
10
9
8
7
6
5
4
3
2
1
0
YY
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
0.002
0.004
0.006
0.008
axis symmetry

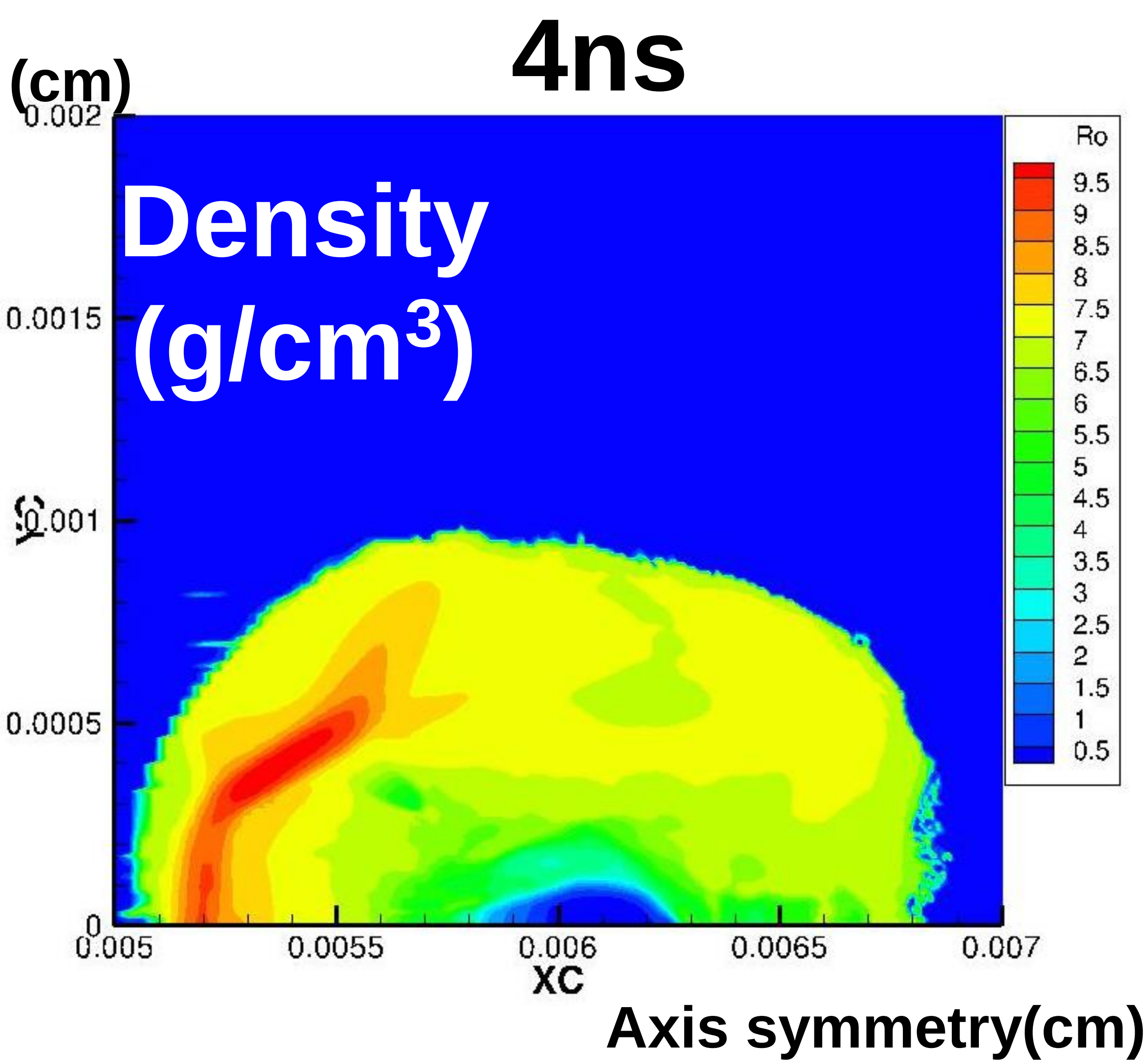


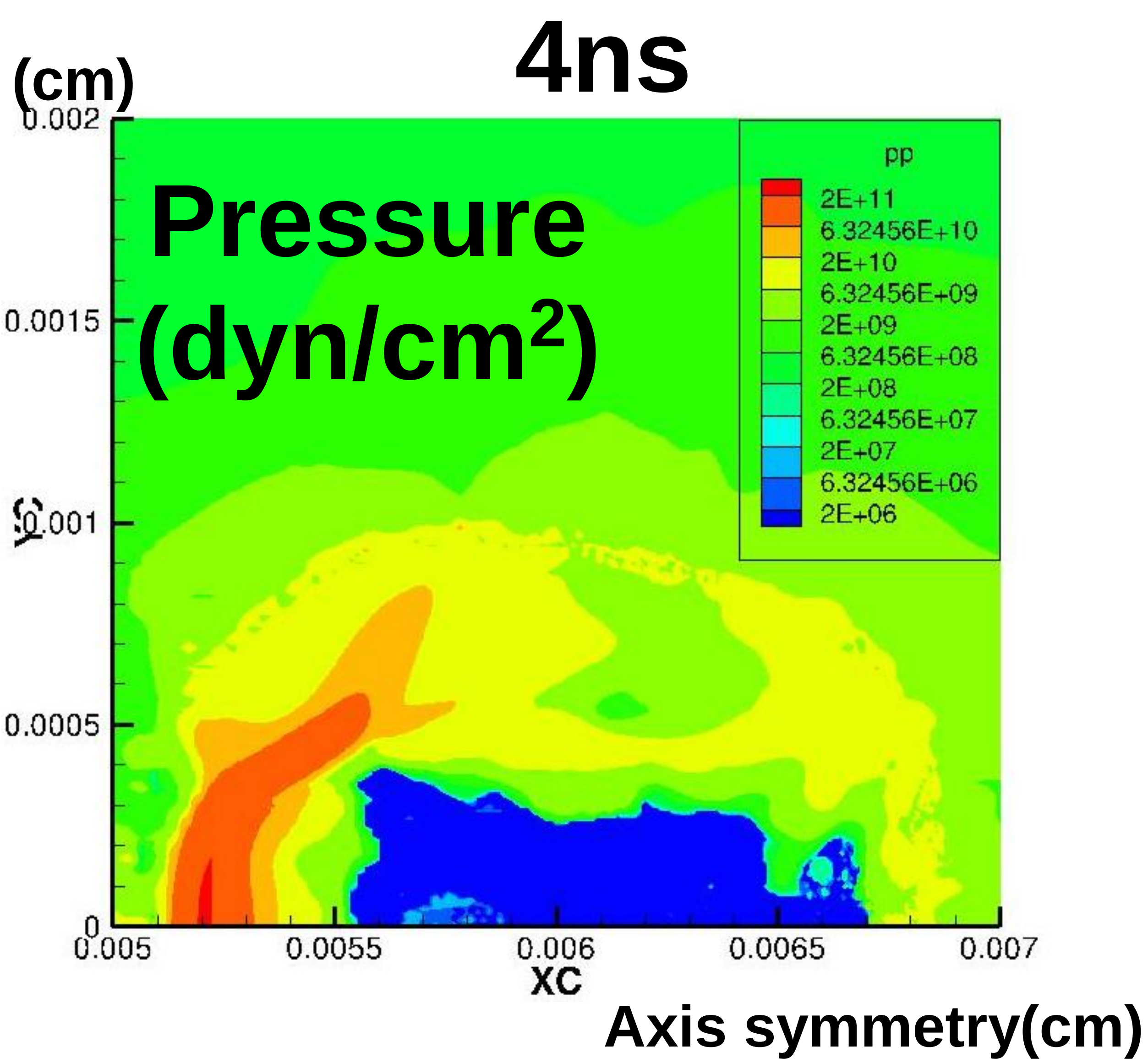
(cm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
YY
up to 10ns
Density
(g/cm3)
Ro
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
axis symmetry
-0.002
-0.001
0
0.001
0.002
XX

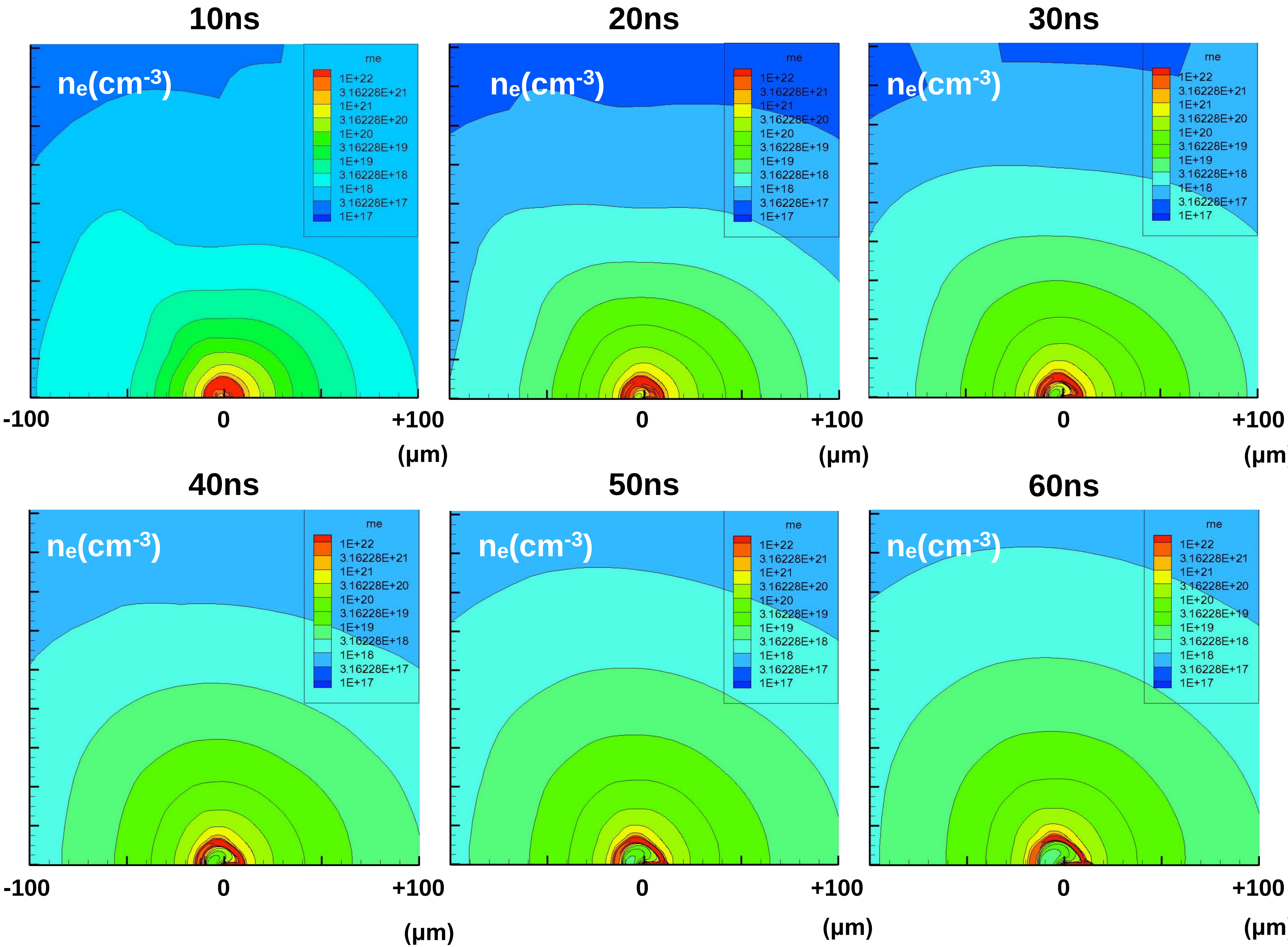


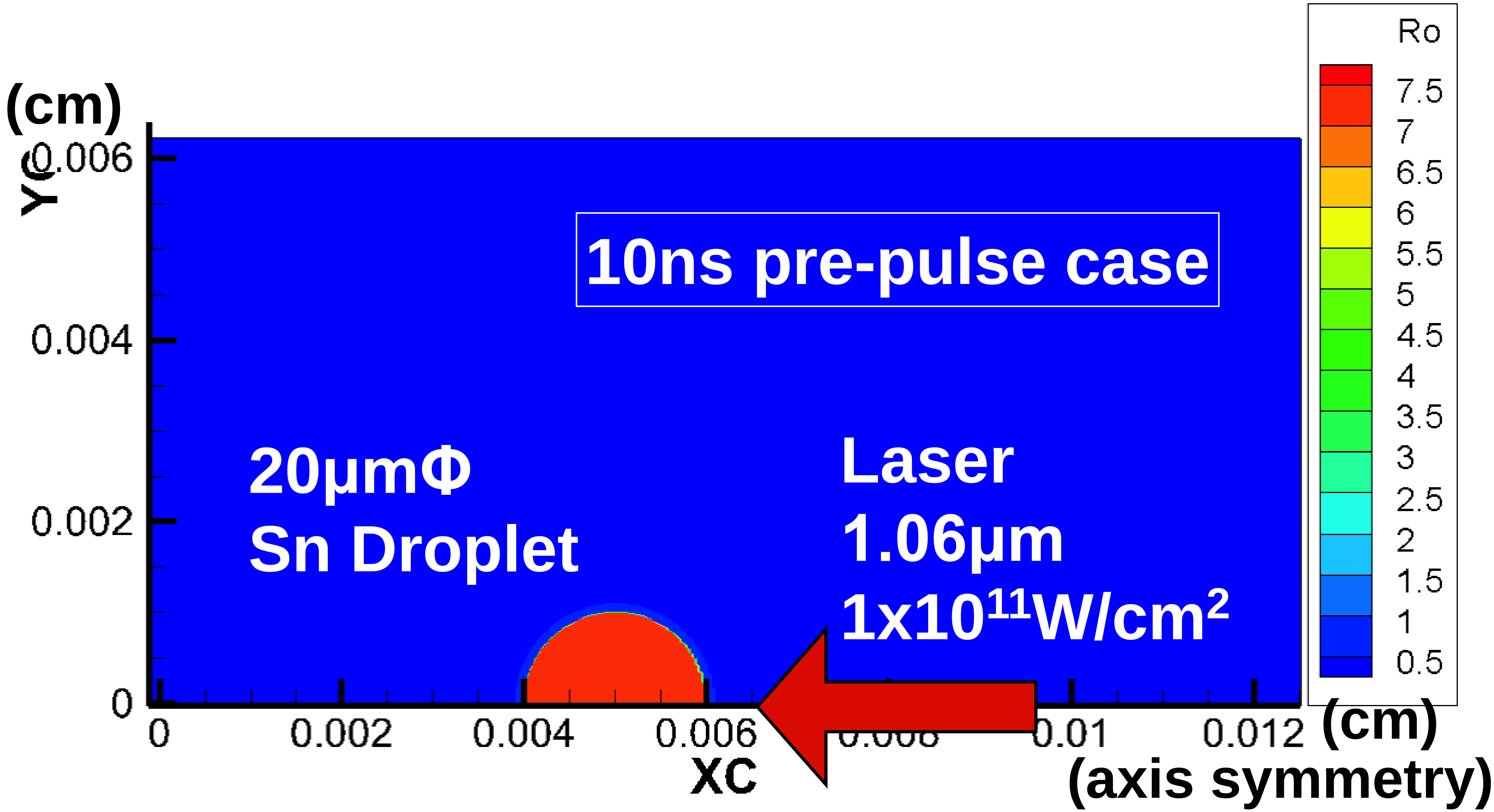
(cm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
YY
up to 10ns
Pressure
(dyn/cm²)
pp
3E+11
9.48683E+10
3E+10
9.48683E+09
3E+09
9.48683E+08
3E+08
9.48683E+07
3E+07
9.48683E+06
3E+06
-0.002
-0.001
0
0.001
0.002
XX
axis symmetry

After shock passed, the shell-void structure is formed.

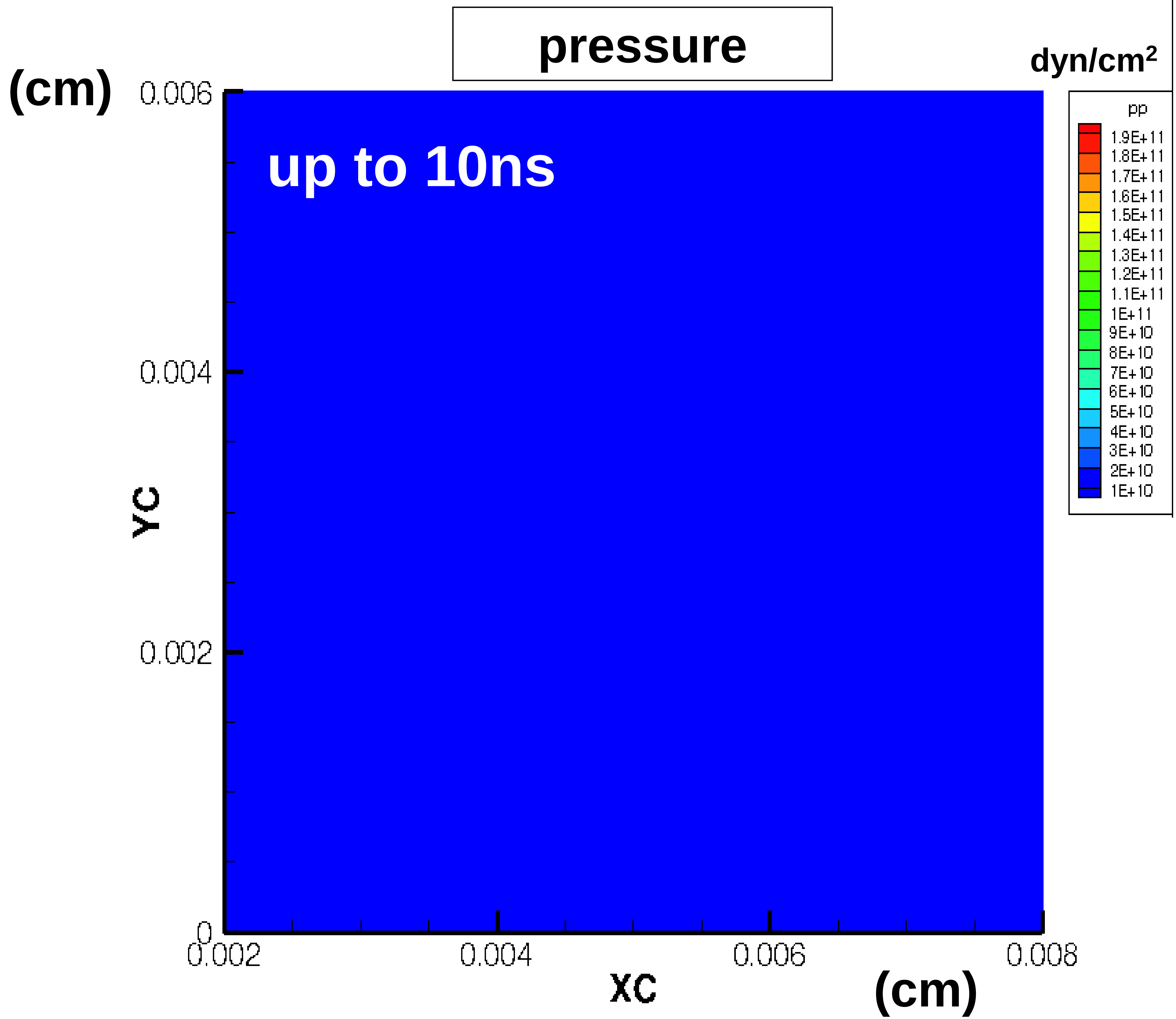




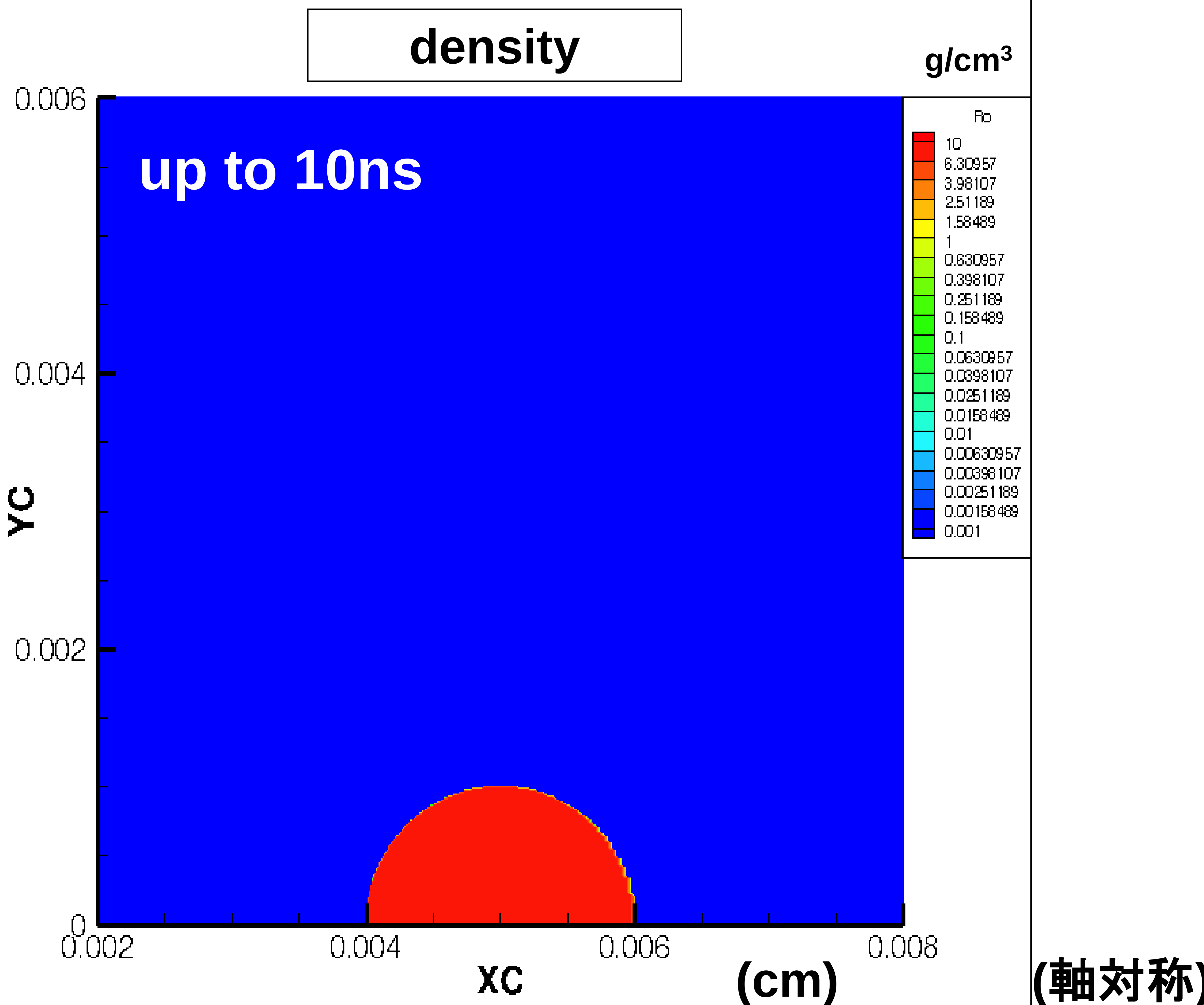

10ns
20ns
30ns
40ns
50ns
60ns
ne(cm-3)
me
1E+22
3.16228E+21
1E+21
3.16228E+20
1E+20
3.16228E+19
1E+19
3.16228E+18
1E+18
3.16228E+17
1E+17
-100
0
+100
(μm)



(cm)
YC
0.006
0.004
0.002
0
10ns pre-pulse case
20μmΦ
Sn Droplet
Laser
1.06μm
1x10^11W/cm^2
0
0.002
0.004
0.006
0.01
0.012
XC
(cm)
(axis symmetry)
Ro
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5



pressure
dyn/cm2
(cm)
up to 10ns
pp
1.9E+11
1.8E+11
1.7E+11
1.6E+11
1.5E+11
1.4E+11
1.3E+11
1.2E+11
1.1E+11
1E+11
9E+10
8E+10
7E+10
6E+10
5E+10
4E+10
3E+10
2E+10
1E+10
0.006
0.004
0.002
0
YC
0.002
0.004
0.006
0.008
XC
(cm)


density
g/cm3
up to 10ns
Ro
10
6.30957
3.98107
2.51189
1.58489
1
0.630957
0.398107
0.251189
0.158489
0.1
0.0630957
0.0398107
0.0251189
0.0158489
0.01
0.00630957
0.00398107
0.00251189
0.00158489
0.001
0.006
0.004
0.002
0
YC
0.002
0.004
0.006
0.008
XC
(cm)
(軸対称)

How to increase the EUV conversion efficiency (CE)

EUV[1)]
Conversion efficiency (CE)

[1)]13.5nm wavelength with 2% bandwidth

= **Laser absorption fraction** × **Conversion efficiency to radiation** × **EUV spectral efficiency**

	Laser absorption fraction	Conversion efficiency to radiation	EUV spectral efficiency
	absorbed laser energy / input laser energy	x-ray emission energy / inputed energy into plasma	EUV emission energy / x-ray emission energy
past: 3% =	50%	50%	12%
current: 5% =	80%	>50%	12%

achieved

NEXT target

Summary and conclusions

- We have conducted simulation research for EUV lithography. EUV output is increasing. However it is not enough for mass production.

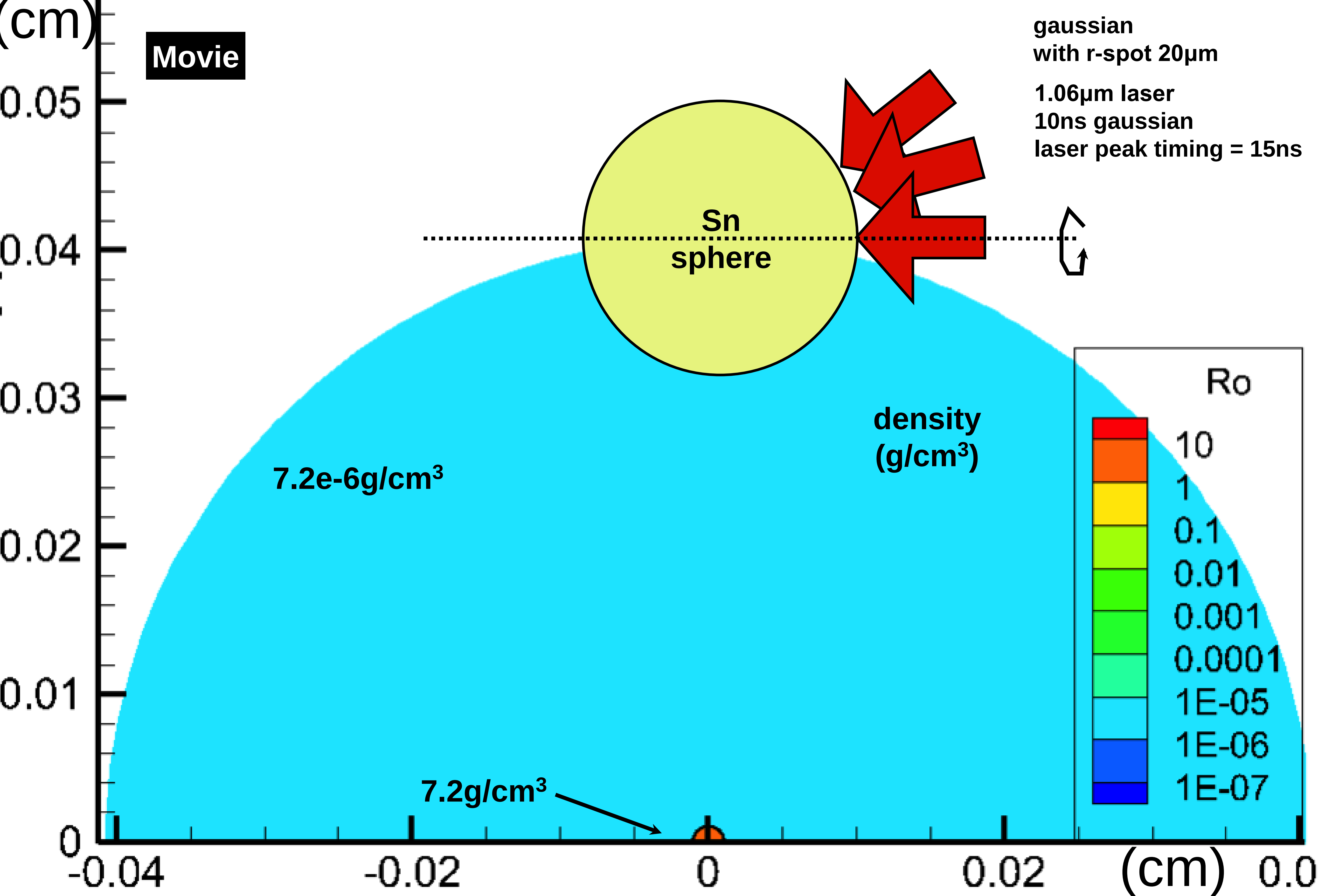
- We have improved the equation of state (EOS) and opacity data tables that are used in the R. hydro code.
- We have developed 2D radiation hydrodynamics code in the conservative form
- We have developed M1 radiation transport routine to simulate the radiation transport accurately.

- We will conduct μsec order calculation for simulating EUV and debris emissions in the double pulse scheme.

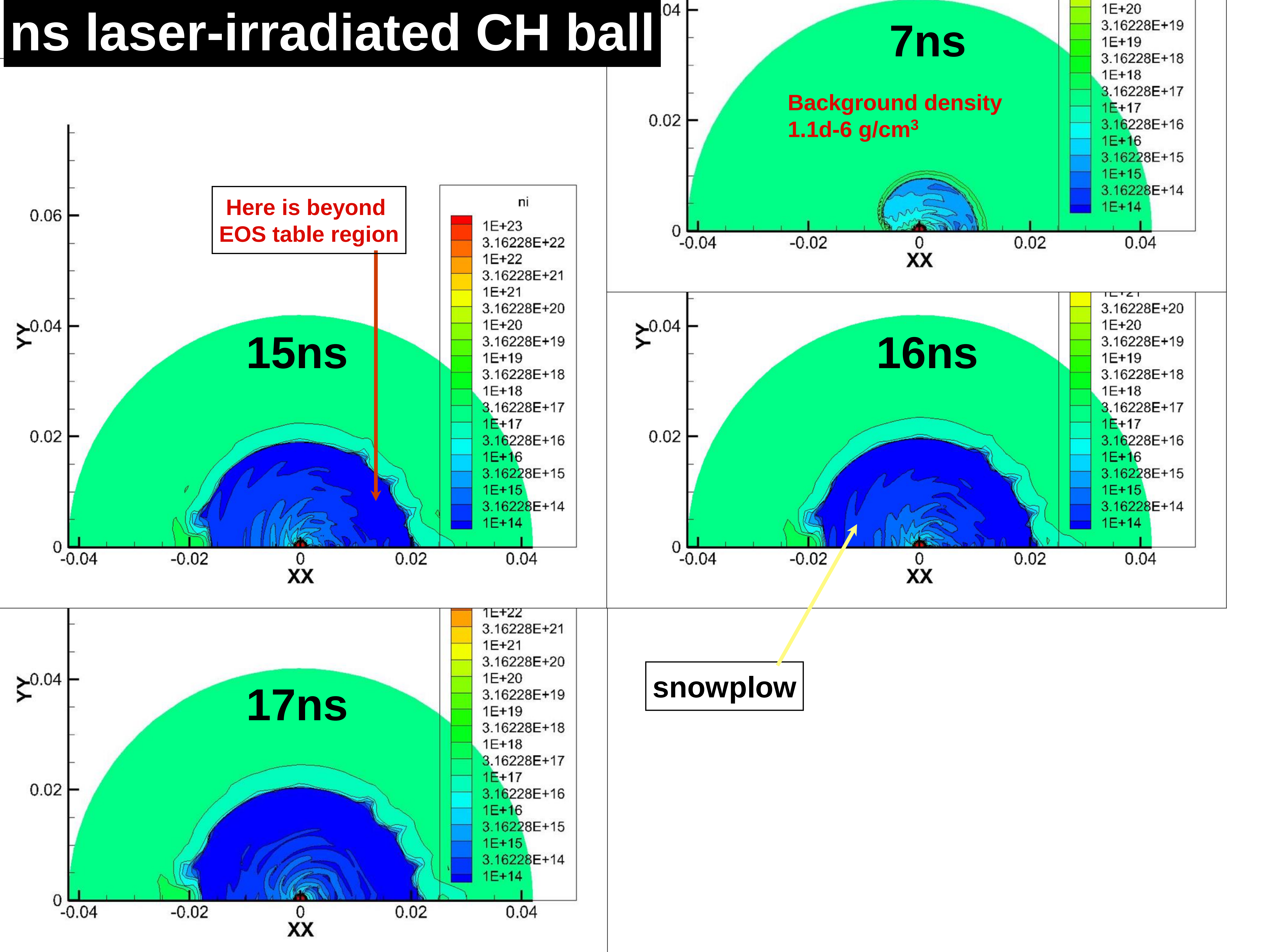
- We would like to use our radiation hydro code for further optimization.

- **additional slides**

ns laser-irradiated tin droplet

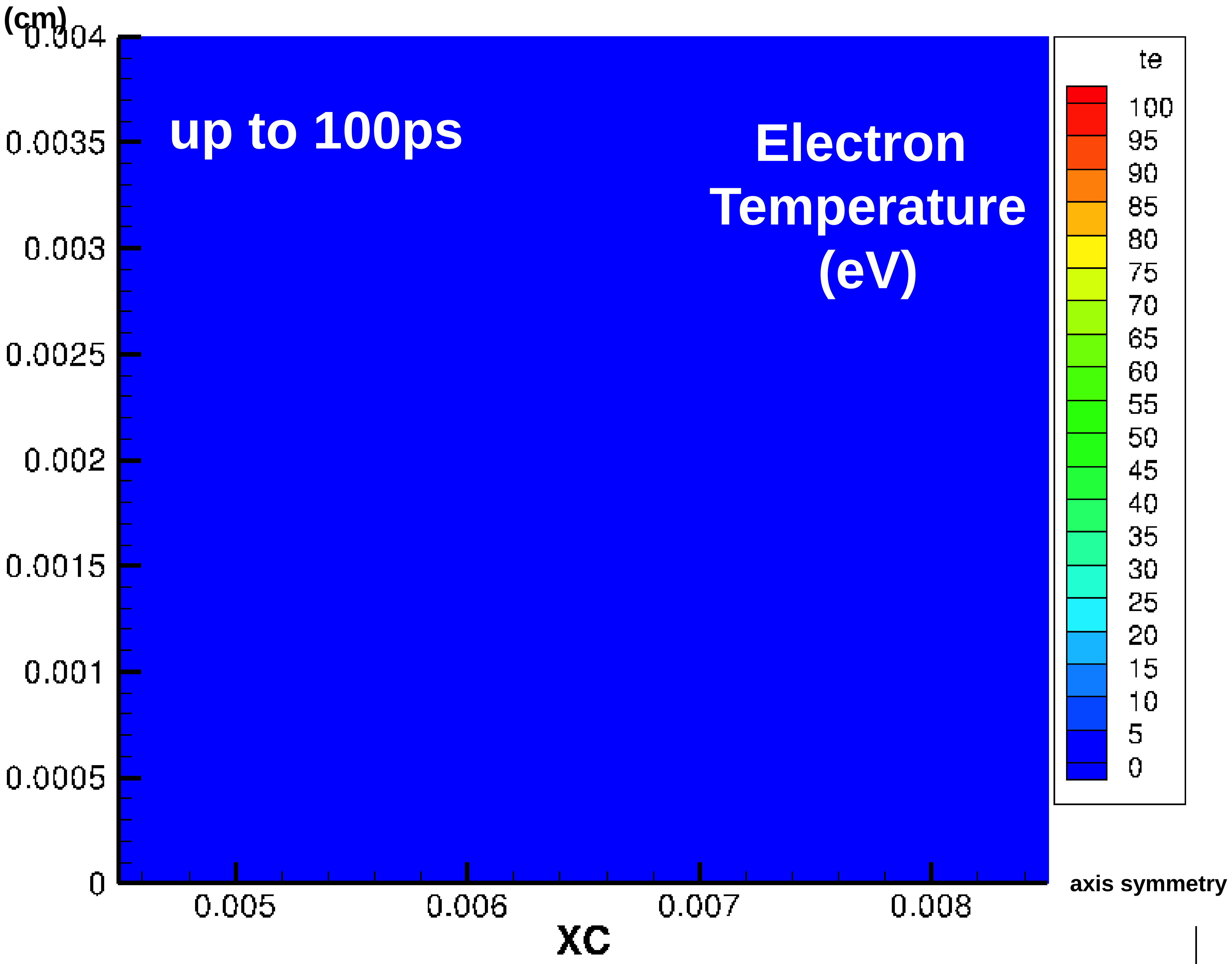


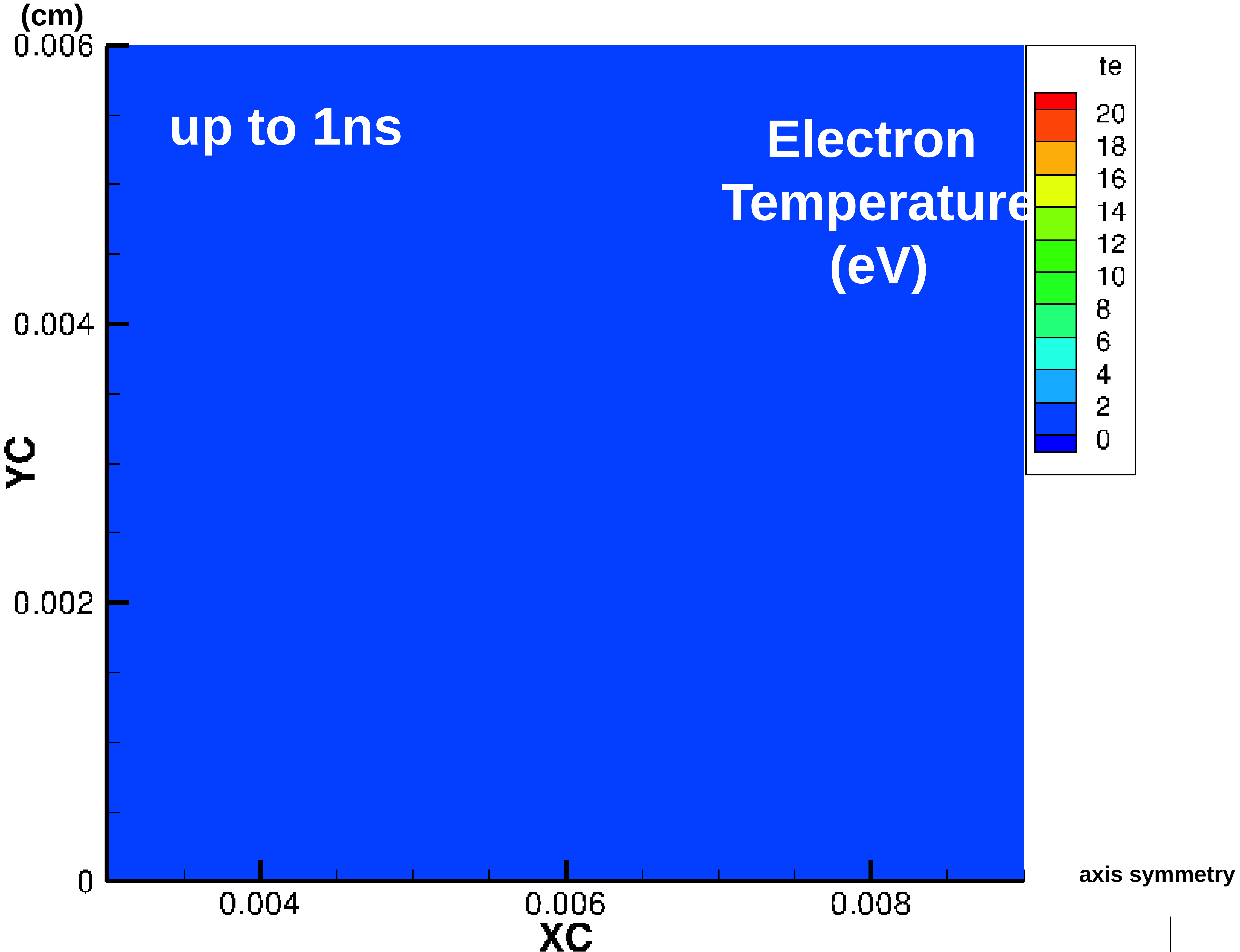
ns laser-irradiated CH ball

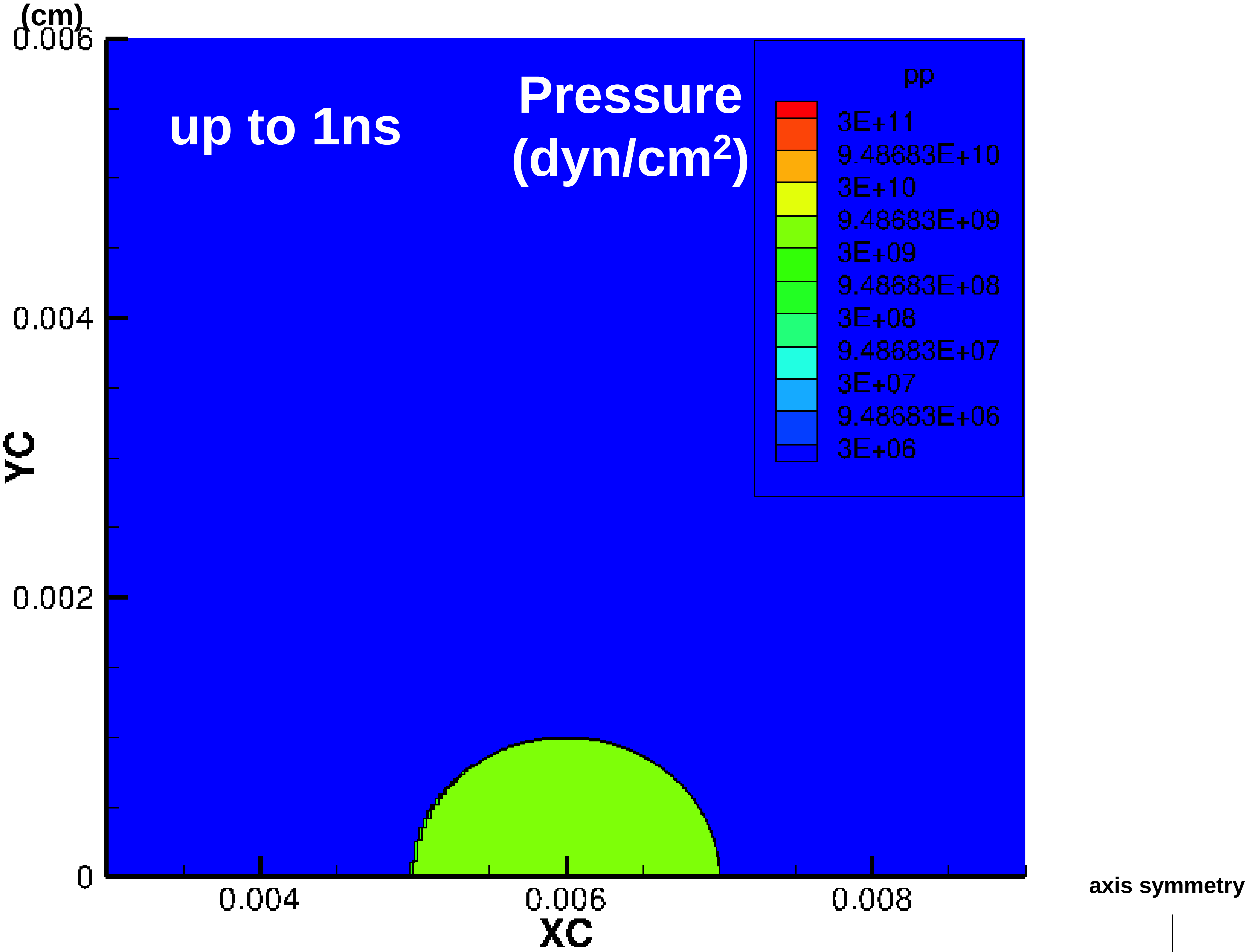


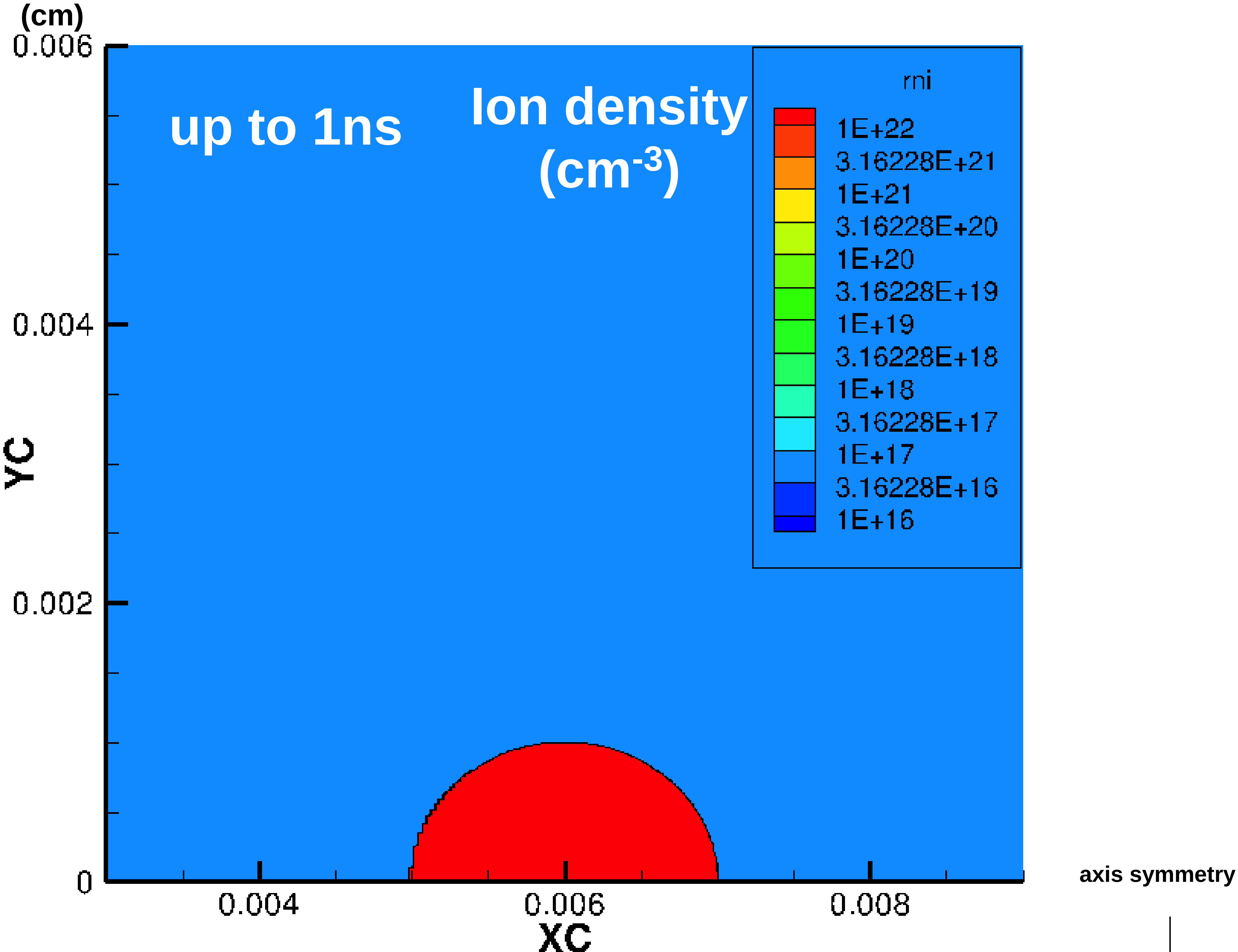
10ps pre-pulse

M1- transport


(cm)
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
up to 100ps
Electron
Temperature
(eV)
te
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0.005
0.006
0.007
0.008
XC
axis symmetry


(cm)
0.006
0.004
0.002
0
YC
up to 1ns
Electron
Temperature
(eV)
te
20
18
16
14
12
10
8
6
4
2
0
0.004
0.006
0.008
XC
axis symmetry


(cm)
0.006
0.004
0.002
0
YC
0.004
0.006
0.008
XC
up to 1ns
Pressure
(dyn/cm²)
pp
3E+11
9.48683E+10
3E+10
9.48683E+09
3E+09
9.48683E+08
3E+08
9.48683E+07
3E+07
9.48683E+06
3E+06
axis symmetry



(cm)
0.006
0.004
0.002
0
YC
up to 1ns
Ion density
(cm-3)
rni
1E+22
3.16228E+21
1E+21
3.16228E+20
1E+20
3.16228E+19
1E+19
3.16228E+18
1E+18
3.16228E+17
1E+17
3.16228E+16
1E+16
0.004
0.006
0.008
XC
axis symmetry